X-RAY POWERFUL DIAGNOSTICS FOR HIGHLY-IONIZED PLASMAS: HE-LIKE IONS

D. Porquet[1,5], R. Mewe[2], J.S. Kaastra[2], J. Dubau[3,5], and A.J.J. Raassen[4,2]

[1]Service d'Astrophysique, CEA Saclay, 91191 Gif-sur-Yvette Cedex, France
[2]SRON, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
[3]LSAI, U.M.R. 8624, CNRS, Université de Paris Sud, 91405 Orsay Cedex, France
[4]Astronomical Institute "Anton Pannekoek" , 1098 SJ Amsterdam, The Netherlands
[5]LUTH, F.R.E. 2462, Observatoire de Paris, section de Meudon, 92195 Meudon Cedex

Abstract

The calculations of the ratios of the Helium-like ion X-ray lines from C V to Si XIII are revisited in order to apply the results to density, temperature and ionization process diagnostics of data from high-resolution spectroscopy of the new generation of X-ray satellites: *Chandra* and *XMM-Newton*. Comparing to earlier computations, Porquet & Dubau (2000), the best experimental values are used for radiative transition probabilities. The influence of an external radiation field (photo-excitation), the contribution from unresolved dielectronic satellite lines and the optical depth are taken into account. These diagnostics could be applied to collision-dominated plasmas (e.g., stellar coronae), photo-ionized plasmas (e.g., "Warm Absorber" in AGNs), and transient plasmas (e.g., SNRs).

Key words: atomic data – atomic process – line: formation – techniques: spectroscopic – X-rays

1. Introduction

With the advent of a new generation of X-ray satellites (Chandra and XMM-Newton), X-ray spectroscopy for extra-solars objects with unprecedented spectral resolution and high S/N is now possible for the first time. Various plasma diagnostics are accessible such as those based on the line ratios of He-like ions. The wavelength ranges of the RGS (6-35 Å), of the LETGS (2-175 Å), and of the HETGS (MEG range: 2.5-31 Å; HEG range: 1.2-15 Å) contain the Helium-like line "triplets" from C V (or N VI for the RGS, and for the HETGS-HEG) to Si XIII (Table 1). The ratios of these lines was already widely used for solar plasma diagnostics (e.g., Mewe & Schrijver 1978a, 1978b, 1978c; Doyle 1980; Pradhan & Shull 1981).

The analysis of the He-like "triplet" is a powerful tool in the analysis of the high-resolution spectra of a variety of plasmas such as:

- collisional plasmas: *e.g., stellar coronae (OB stars, late type stars, active stars, ...)*
- photo-ionized or hybrid plasmas (photo-ionization + collisional ionization): *e.g., "Warm Absorber" (in AGNs), X-ray binaries, ...*
- out of equilibrium plasmas: *e.g., SNRs, ...*

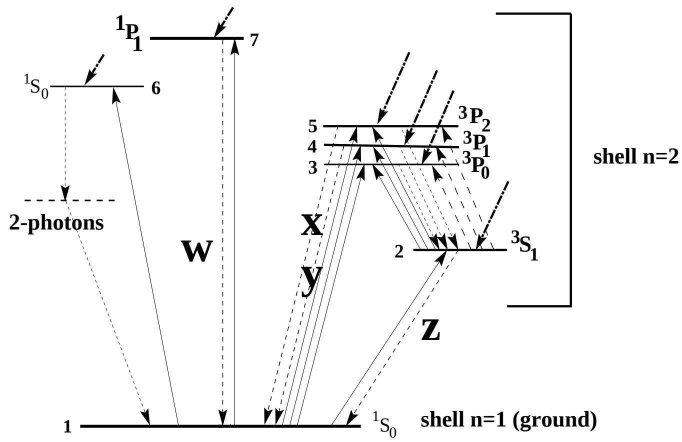

Figure 1. Simplified level scheme for Helium-like ions. **w** *(or r),* **x,y** *(or i), and* **z** *(or f): resonance, intercombination, and forbidden lines, respectively. Full upward arrows: collisional excitation transitions, broken arrows: radiative transitions (including photo-excitation from $2\,^3S_1$ to $2\,^3P_{0,1,2}$ levels, and 2-photon continuum from $2\,^1S_0$ to the ground level), and thick skew arrows: recombination (radiative and dielectronic) plus cascade processes.*

2. Diagnostics

In the X-ray range, the three most intense lines of Helium-like ions ("triplet") are: the *resonance* line (w, also called r: 1s$^2\,^1S_0$ – 1s2p$\,^1P_1$), the *intercombination* lines ($x+y$, also called i: 1s$^2\,^1S_0$ – 1s2p$\,^3P_{2,1}$) and the *forbidden* line (z, also called f: 1s$^2\,^1S_0$ – 1s2s$\,^3S_1$). They correspond to transitions between the n=2 shell and the n=1 ground-state shell (see Figure 1).

Gabriel & Jordan (1969) introduced the techniques to determine, from the ratios R and G, electron density and temperature of the Solar corona:

$$R\ (n_e)\ =\ \frac{z}{(x+y)} \qquad\qquad G\ (T_e) = \frac{(x+y)+z}{w} \qquad (1)$$

2.1. Density diagnostic

In the low-density limit, all n=2 states are populated directly or via upper-level radiative cascades by electron impact from the He-like ground state and/or by (radiative and dielectronic) recombination of H-like ions (see Fig-

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Table 1. Wavelengths in Å of the three main X-ray lines of C V, N VI, O VII, Ne IX, Mg XI *and* Si XIII *(from Vainshtein & Safronova 1978).*

line	label	C V	N VI	O VII	Ne IX	Mg XI	Si XIII
resonance	w (r)	40.279	28.792	21.603	13.447	9.1681	6.6471
inter-	x	40.711	29.074	21.796	13.548	9.2267	6.6838
combination	y	40.714	29.076	21.799	13.551	9.2298	6.6869
forbidden	z (f)	41.464	29.531	22.095	13.697	9.3134	6.7394

ure 1). These states decay radiatively directly or by cascades to the ground level. The relative intensities of the three intense lines are then independent of density. As $n_{\rm e}$ increases from the low-density limit, some of these states (1s2s ^{3}S$_1$ and ^{1}S$_0$) are depleted by collisions to the nearby states where $n_{\rm crit}$ C=A, with C being the collisional coefficient rate, A being the radiative transition probability from n=2 to n=1 (ground state), and $n_{\rm crit}$ being the critical density. Collisional excitation depopulates first the 1s2s ^{3}S$_1$ level (upper level of the *forbidden* line) to the 1s2p ^{3}P$_{0,1,2}$ levels (upper levels of the *intercombination* lines). The intensity of the *forbidden* line decreases while those of the *intercombination* lines increase, hence implying a reduction of the ratio R (according to Eq. 1), over approximately two or three decades of density (see Fig. 2).

For much higher densities, 1s2s ^{1}S$_0$ is also depopulated to 1s2p^{1}P$_1$, and the *resonance* line becomes sensitive to the density.

However caution should be taken for low-Z ions (i.e. C V, N VI, O VII) since in case of an intense UV radiation field, the photo-excitation between the ^{3}S term and the ^{3}P term is not negligible. This process has the same effect on the *forbidden* line and on the *intercombination* line as the collisional coupling, i.e. lowering of the ratio R, and thus could mimic a high-density plasma. It should be taken into account to avoid any misunderstanding between a high-density plasma and a high radiation field (see §5.1 for more details).

2.2. Temperature and ionization process diagnostics

The ratio G (see Eq. 1) is sensitive to the electron temperature since the collisional excitation rates have not the same dependence with temperature for the *resonance* line as for the *forbidden* and *intercombination* lines.

In addition, as detailed in Porquet & Dubau 2000 (see also Mewe 1999, and Liedahl 1999), the relative intensity of the *resonance* w line, compared to the *forbidden* z and the *intercombination* $x{+}y$ lines, contains information about the ionization processes that occur: a strong *resonance* line compared to the *forbidden* or the *intercombination* lines corresponds to collision-dominated plasmas. It leads to a ratio of $G=((x+y)+z)/w$ ∼1. On the contrary, a weak *resonance* line corresponds to plasmas dominated by the photo-ionization $G=((x+y)+z)/w$ >4. An illustration is given Figure 2.

However, as mentionned for the density diagnostic, caution should be taken since photo-excitation can mimic a hybrid plasmas, i.e. photo-ionization plus collisional ionization, e.g. shock or starburst (see §5.2).

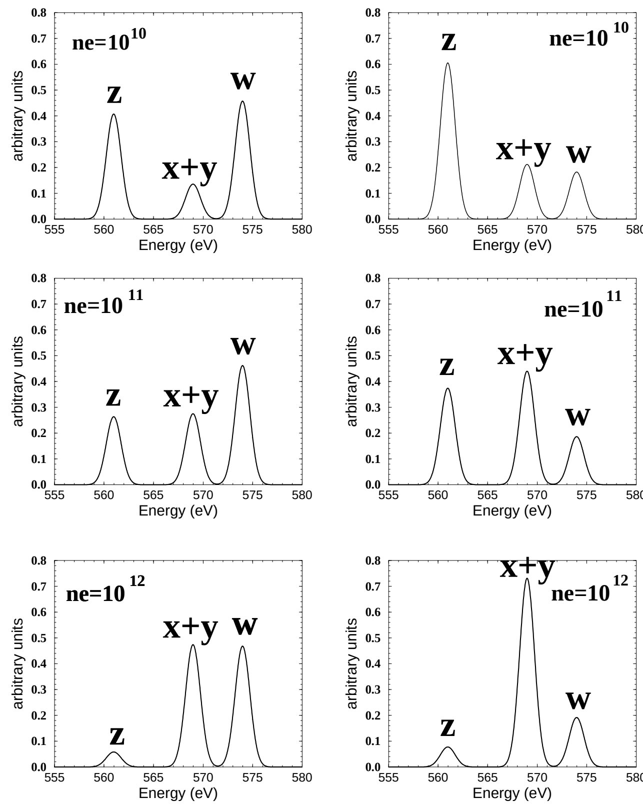

Figure 2. O VII *theoretical spectra constructed using the RGS (XMM) resolving power (E/ΔE) for three values of density (in cm^{-3}). This corresponds (approximatively) to the range where the ratio* **R** *is very sensitive to density.* **z**: *forbidden lines,* **x+y**: *intercombination lines and* **w**: *resonance line. At left: "hybrid plasma" at T$_{\rm e}$=1.5 10^6 K; At right: "pure" photoionized plasma at T$_{\rm e}$=10^5 K). Note: the intensities are normalized in order to have the sum of the lines equal to the unity.*

3. Blended dielectronic satellite lines

The influence of the blending of dielectronic satellite lines for the *resonance*, the *intercombination* and the *forbidden* lines has been taken into account when their contribution is not negligible in the calculation of R and G, affecting the inferred electron temperature and density. This is the case for the high-Z ions produced in a collisional plasma, i.e. Ne IX, Mg XI, and Si XIII (Z=10, 12, and 14, respectively).

$$R=\frac{z+satz}{(x+y)+satxy} \qquad (2)$$

$$G=\frac{(z+satz)+((x+y)+satxy)}{(w+satw)}, \qquad (3)$$

where *satz*, *satxy* and *satz* are respectively the contribution of blended dielectronic satellite lines to the *forbidden* line, to the *intercombination* lines, and to the *resonance* line, respectively. One can note that at very high density the ^{3}P levels are depleted to the ^{1}P level, and in that case $x+y$ decreases and R tends to $satz/satxy$.

The intensity of a dielectronic satellite line arising from a doubly excited state with principal quantum number n in a Lithium-like ion produced by dielectronic recombination of a He-like ion is given by:

$$I_s = N_{\rm He}\ n_{\rm e}\ C_s, \tag{4}$$

where $N_{\rm He}$ is the population density of the considered He-like ion in the ground state 1s^2 with statistical weight g_1 (for He-like ions $g_1 = 1$).
The rate coefficient (in cm^3 s^{-1}) for dielectronic recombination is given by (Bely-Dubau et al. 1979):

$$C_s = 2.0706\ 10^{-16}\ \frac{e^{-E_s/kT_{\rm e}}}{g_1 T_{\rm e}^{3/2}}\ F_2(s), \tag{5}$$

where E_s is the upper energy level of the satellite line s with statistical weight g_s above the ground state 1s^2 of the He-like ion. $T_{\rm e}$ is the electron temperature in K, and $F_2(s)$ is the so-called line strength factor (often of the order of about 10^{13} s^{-1} for the stronger lines) given by

$$F_2(s) = \frac{g_s A_a A_r}{(A_a + \sum A_r)}, \tag{6}$$

where A_a and A_r are transition probabilities (s^{-1}) by auto-ionization and radiation, and the summation is over all possible radiative transitions from the satellite level s.

Since the contribution of the blended dielectronic satellite lines depends on the spectral resolution considered, we have estimated the ratios R and G for four specific spectral resolutions (FWHM): RGS-1 at the first order, LETGS, HETGS-MEG, and HETGS-HEG (Porquet, Mewe et al 2001). At the temperature at which the ion fraction is maximum for the He-like ion (see e.g. Mazzotta et al. 1998), the differences between the calculations for R (for G) with or without taking into account the blended dielectronic satellite lines are only of about 1% (9%), 2% (5%), and 5% (3%) for Ne IX, Mg XI, and Si XIII at the low-density limit and for T_{rad}=0 K, respectively.

However, for photo-ionized plasmas where recombination prevails and the temperature is much lower (e.g., T$\lesssim$0.1T$_m$), the effect on R and G can be much bigger since $I_{sat}/I_w \propto T^{-1} e^{(E_w-E_{sat})/k{\rm T}}$. For very high density $n_{\rm e}$ the contribution of the blended dielectronic satellite lines to the forbidden line leads to a ratio R which tends to $satz/satxy$, hence decreases much slower with $n_{\rm e}$ than in the case where the contribution of the blended DR satellites is not taken into account.

4. Optical depth

If the optical depth of the resonance line is not taken into account, the calculated ratio G could be overestimated (inferred temperature underestimated) when the optically-thin approximation is no longer valid. This has been estimated with an *escape-factor method*, e.g., for the case of a *Warm Absorber in an AGNs* (Porquet, Kaastra, Mewe, Dubau 2002).

5. Radiation field (photo-excitation)

5.1. Influence on density diagnostic

A strong radiation field can mimic a high density if the photo-excitation ^{3}S$_1$ level (f line) → ^{3}P$_{0,1,2}$ levels (i lines) exceeds the electron collisional excitation. ex: ζ Puppis (Kahn et al. 2001, Cassinelli et al. 2001). Rate of photo-excitation (in s^{-1}) (Mewe & Schrijver 1978a) in a stellar photospheric radiation field with effective black-body radiation temperature T_{rad} is written as:

$$B_{mp_k} = \frac{W A_{p_k m}(w_{p_k}/w_m)}{exp\left(\frac{\Delta E_{mp_k}}{kT_{\rm rad}}\right) - 1}, \tag{7}$$

where A and B are the Einstein coefficients and the radiation is diluted by a factor W given by

$$W = \frac{1}{2}\ \left[1 - \left(1 - \left(\frac{r_*}{r}\right)\right)^{1/2}\right], \tag{8}$$

• **W=1/2** (close to the stellar surface, $r = r_*$; e.g., Capella and Procyon: Audard et al. 2001, Mewe et al. 2001, Ness et al. 2001).
• **W<< 1/2** (radiation originates from another star at larger distance; e.g., Algol, where K-star is irradiated by B-star, $W \simeq 0.01$: Ness et al. 2002).

Porquet et al. (2001) showed that photo-excitation is important for C V, N VI, O VII for T$_{rad}$ ≥(5-10) 10^3 K (see Fig. 3), and for higher-Z ions when T$_{rad}$ ≥ few 10^4 K.

5.2. Influence on ionization process diagnostic

Recently, Kinkhabwala et al. (2002), pointed out the important effect of the photo-excitation in the high Rydberg series lines. Indeed, the ratio of high-n lines to Lyα bring evidence for photo-excitation in Warm Absorber Seyfert 2. They clearly showed that in addition to photo-ionization (treated in Porquet & Dubau 2000), photo-excitation process is sufficient to fit the data of Seyfert galaxies without needing an additional collisional ionization process (e.g. shock or starburst). Then both photo-ionization and photo-excitation are needed to inferred unambiguously the ionization process occurring in the plasmas.

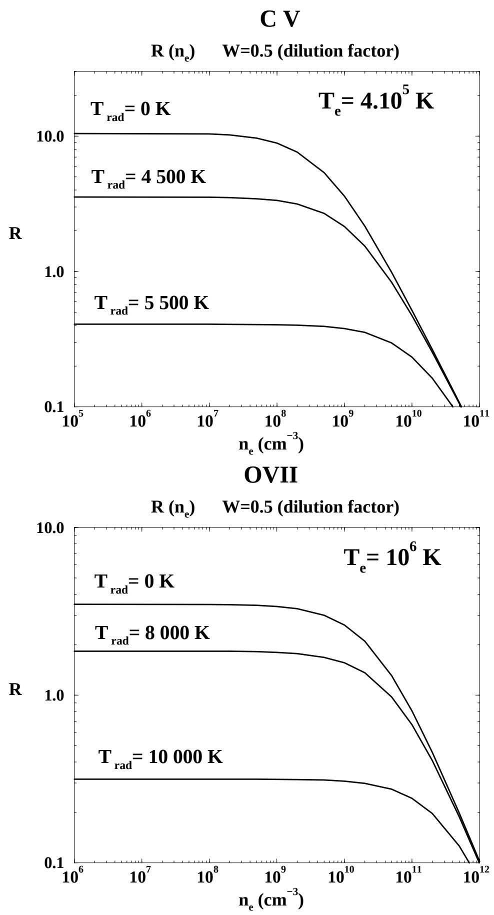

Figure 3. Ratio $R(n_e)$=$z/(x+y)$ in dependence of stellar radiation field for C V *(top) and* O VII *(bottom). Note that, e.g. for* O VII *a radiation field with effective temperature of 10^4 K can mimic a density of about $3\,10^{11}$ cm^{-3}.*

6. Conclusion

Helium-like density and temperature diagnostics has now become a powerful tool in the analysis of the high resolution *Chandra* and *XMM-Newton* X-ray spectra (Porquet & Dubau 2000). Therefore, we have revisited the calculations of the ratios $R = z/(x+y)$ and $G = ((x+y)+z)/w$ of the z, $(x+y)$, *and* w *"triplet" lines of the He-like ions* C V, N VI, O VII, Ne IX, Mg XI, Si XIII, taking into account all relevant processes and improved atomic data.

The calculations were done for optically thin plasmas in collisional ionization equilibrium (e.g., stellar coronae: Porquet, Mewe et al. 2001). The influence of an external radiation field on the depopulation of the upper level of z is considered which can be important for hot OB or F stars (e.g., ζ Puppis, Procyon, and Algol). In preparation are improved calculations for photo-ionized and hybrid plasmas (e.g., warm absorber in AGNs: Porquet, Kaastra, Mewe, Dubau 2002), and will be extended to transient ionization plasmas (young SNRs: Kaastra, Mewe, Porquet, Raassen 2002), where inner-shell ionization of the Li-like ion can contribute significantly to the intensity of the forbidden line (see also Mewe 2002).

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References

Audard, M. et al. (2001), A&A, 365, L329
Bely-Dubau, F., Gabriel, A. H., Volonté, S. 1979, MNRAS, 189, 801
Cassinelli J. P., Miller N. A., Waldron W. L., MacFarlane J. J., Cohen D. H. (2001), ApJ, 554, L55
Doyle J.G. (1980), A&A, 87, 183
Gabriel A.H. & Jordan, C. (1969), MNRAS, 145, 241
Kaastra J. S, Mewe R., Porquet D., Raassen A. J. J. (2002), in preparation (Paper IV)
Kahn S. M. et al. (2001), A&A, 365, L312
Kinkhabwala et al. 2002, these proceedings
Liedahl D. A., 1999, X-Ray Spectroscopy in Astrophysics, 189
Mazzotta P. et al. 1998, A&AS, 133, 403
Mewe R. & Schrijver J. (1978a), A&A, 65, 99
Mewe R. & Schrijver J. (1978b), A&A, 65, 115
Mewe R. & Schrijver J. (1978c), A&AS, 45, 11
Mewe R., 1999, X-Ray Spectroscopy in Astrophysics, 109
Mewe R., Raassen A.J.J., Drake J.J., Kaastra J.S., van der Meer R.L.J., Porquet D. (2001), A&A, 368, 888
Mewe R. 2002, these proceedings
Ness J.-U., Mewe R., Schmitt J.H.M.M., Raassen A.J.J., Porquet D. et al. (2001), A&A, 367, 282
Ness J.-U. et al. (2002), in preparation
Porquet D. & Dubau J. (2000), A&AS, 143, 495 (Paper I)
Porquet D., Mewe R., Dubau J., Raassen A. J. J., Kaastra J. S (2001), A&A, 376, 1113 (Paper II)
Porquet D., Kaastra J. S, Mewe R., Dubau J. (2002), in preparation (Paper III)
Pradhan A. K. & Shull J. M. (1981), ApJ, 249, 821
Vainshtein L. A., Safronova U. I., 1978, Atomic Data and Nuclear Data Tables, 21, 49